LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-PROC-207143

Hard X-ray Optics for Astronomy and the Laboratory

M. Pivovaroff

October 11, 2004

Workshop on Emerging Scientific Opportunities using X-ray Imaging
Lake Geneva, WI, United States
August 29, 2004 through September 1, 2004

Hard X-ray Optics for Astronomy and the Laboratory

Michael Pivovaroff (Lawrence Livermore National Laboratory)

1. Introduction

The hard X-ray regime (10-100 keV) remains one of the last unexplored areas of astronomy. During the next decade, several major observatories will open this new frontier, providing insight into black hole formation, nucleosynthesis and the physics that governs the most energetic quasars. The telescopes rely on grazing incidence optics coated with multilayers, and will require at wavelength calibration of the angular resolution of the mirrors and the reflectivity of their coatings—a task best performed at synchrotron facilities. As mirror fabrication and multilayer development for astronomy has progressed, other applications of these hard X-rays optics has emerged, ranging from radionuclide imaging for biomedical research to collimator optics for X-ray sources to target characterization and diagnostic imaging for the National Ignition Facility (NIF). The resolution, field of view (FOV) and throughput of these systems make them interesting candidates for adaptation to synchrotron beamlines, acting as collimator or collector elements or focusing elements for microscopy.

2. Hard X-ray Astronomy Instrumentation

A. Near-term Missions

During the next ten to fifteen years, NASA, the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA) will all launch large astronomy observatories with hard X-ray telescopes [1-3]. Unlike previous X-ray satellites (*e.g.*, Chandra and XMM-Newton) that have a high energy limit of ~10 keV [4-5], the new missions will have sensitivity up to ~100 keV due to a key innovation in the use of multilayer coatings. Although they have long been used to enhance optical performance at lower energies, it was only recently that Christensen et al. [6] realized that it was possible to construct multilayer coatings with high reflectivity over a broad energy band by varying the thickness of the bi-layer pairs as a function of depth.

B. Calibration Needs

These programs represent a major commitment by the astronomical community and will require extensive calibration of the mirrors to achieve their scientific goals. X-ray telescopes require characterization of their point spread function (PSF) and reflectivity as a function of energy and have traditionally been calibrated at long-beam (> 100 m) facilities specifically designed for this purpose [7,8]. The facilities rely on electron impact sources and monochromators to separate the bright characteristic emission lines from the underlying bremsstrahlung. While the myriad K-, L-, and M-shell lines available below 15 keV provide uniform coverage over the soft X-ray band, achieving similar coverage at harder energies is much more challenging, due to the high-voltage requirement (the voltage should be two to three times higher than the characteristic line emission) and the limited choice in anode materials.

C. The Role of the Synchrotron

Instead, synchrotrons offer a much more flexible alternative for the calibration of the first generation of focusing hard X-ray satellites, as well as the prototype optics necessary for their successful development and fabrication. High-brightness sources like the European Synchrotron Radiation Facility (ESRF), the Super Photon ring-8 GeV (SPring-8), and the Advance Photon Source (APS) allow tuning to any energy in the pass-band, not just those that correspond to K-shell emission lines. The only challenge is that low-divergence monochromatized beam cannot fully illuminate the aperture of the optic. The mirror response, then, is calibrated by scanning the telescope in azimuth across the narrow pencil beam produced by the synchrotron and synthesizing a complete PSF from individual scans. An example of the PSF computed from this approach is shown in Figure 1.

Synchrotrons will also play a unique and irreplaceable role in calibrating the multilayer reflectivity in two distinct ways. First, the atomic data for the materials commonly used in hard X-ray multilayers have only recently begun to be measured at these energies [9]. As shown in Figure 2, models based on theoretical values for scattering factors and mass absorption coefficients do not agree well with experimentally determined properties, partially as a result of not accounting for incoherent (Compton) scattering in the light elements [10]. Second, with the atomic constants accurately determined, multilayer recipes can be optimized and their performance verified at wavelength [e.g., 11].

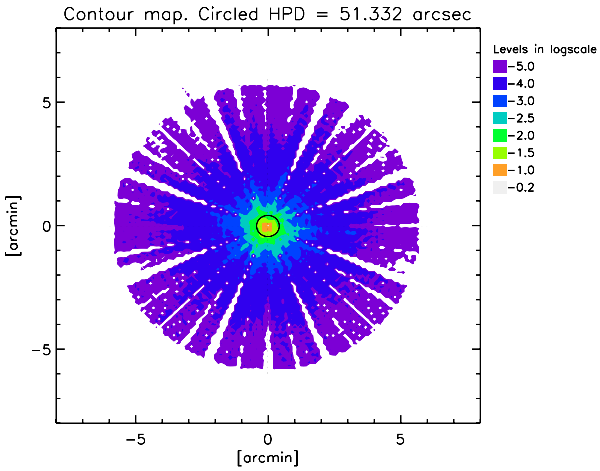

Figure 1: PSF of a prototype hard X-ray telescope measured at ESRF at 40 keV. The map has been synthesized from 360 individual, azimuthal scans. The gaps arise from support structures used in fabrication of the optic.

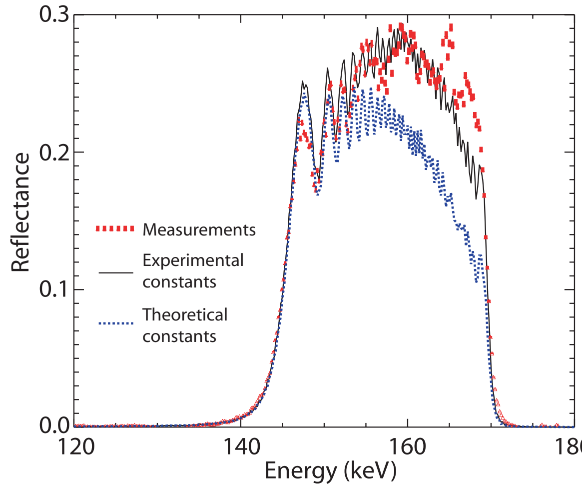

Figure 2: Measured reflectivity of a W/SiC multilayer coating, with best-fit models based on experimentally determined optical constants (solid line) or theoretical ones (dashed line). Data reproduced from ref 9, courtesy of David Windt.

3. Other Applications for Hard X-ray Optics

The significant investment made by the astronomy community in multilayer development and inexpensive substrate manufacturing has enabled the use of hard X-ray optics in a wide variety of disciplines. To highlight potential applications, we consider some projects currently underway at Lawrence Livermore National Laboratory. Although developed for non-synchrotron work, it would be trivial to adopt these optical designs for synchrotron beamlines dedicated to microscopy or for collimator/concentrator elements.

One exciting prospect is building an optic capable of performing *in vivo* radionuclide imaging in small-animals. Animal models, particularly transgenic and knock-out mice, are now being used in every area of biomedical research. By building highly-nested optics (similar to the astronomy telescopes but with a modified optical prescription), it is possible to achieve hundred micron or better resolution with a field of view of ~0.5−2 cm and sufficient sensitivity to perform studies with radiopharmaceuticals tagged with ^{125}I, ^{99m}Tc or ^{95m}Tc [12]. Such an imaging system will improve the spatial resolution by an order of magnitude over that currently provided by the state-of-the-art absorptive collimation techniques.

Several National Ignition Facility (NIF) programs would also benefit from hard X-ray optics that could provide micron or better imaging across a 1−2 mm FOV. On the target fabrication side, a hard X-ray microscope could provide characterization of some of the most challenging high-Z targets [13]. For diagnostics of the actual experiments, Wolter optics with multilayer coatings may deliver higher numbers of photons per resolution element than Fresnel zone plates or schemes utilizing high-magnification point-projection imaging.

4. References

1. http://sci.esa.int/xeus
2. http://constellation.gsfc.nasa.gov/
3. http://www.astro.isas.jaxa.jp/future/NeXT/
4. MC Weisskopf *et al*., Proc SPIE, 4012, 2, (2000).
5. F Jansen *et al.*, Astro & Astroph, 365, L1 (2000).
6. FE Christensen *et al*., Proc SPIE, 1546, 160, (1991).
7. KH Stephan *et al.*, Proc SPIE, 316, 203, (1981).
8. MC Weisskopf & SL O'Dell, Proc SPIE, 3113, 2, (1997).
9. DL Windt *et al*., Appl Optics, 42, 2415, (2003).
10. DL Windt *et al*., Proc. SPIE, 5168, 35, (2003).
11. FE Christensen *et al.*, NIM A, 451, 572-581, (2000).
12. MJ Pivovaroff *et al*., Proc. SPIE, 5199, 147, (2003).
13. W Nederbragt, Proc 18th Meeting of Amer Soc Prec Engineer, 111 (2003).

5. Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.